Expanding Remote Science Operations Capabilities Onboard the International Space Station

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Abstract—EXPRESS Racks have been supporting payload science operations onboard the International Space Station (ISS) since April of 2001[1,2]. EXPRESS is an acronym that stands for "EXpedite the PRocessing of Experiments to Space Station." This name reflects NASA's focus to simplify the process of manifesting experiments and maximizing scientific research capabilities by providing a robust, remotely operated payload support platform. The EXPRESS Rack System was developed by NASA's Marshall Space Flight Center (MSFC) and built by The Boeing Company in Huntsville, Alabama. Eight EXPRESS racks were built and five are currently onboard the ISS supporting science operations. The design and development of the EXPRESS Rack System is a long story that has been documented in previous publications. This paper briefly describes the facilities used to develop and verify flight software, test operational capabilities. It then traces the advancements made in the operational capabilities of the EXPRESS Racks from the time they were launched on STS-100 through the present. The paper concludes with a description of potential enhancements that will make the EXPRESS racks one of the most advanced and capable remote science platforms ever developed.

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1. INTRODUCTION

In April of 2005, the ISS US Laboratory module Destiny will have been supporting science research in Earth orbit for over four years. That month will also mark the fourth anniversary for one of the most important elements for conducting remote science operations on the ISS, The EXPRESS Rack. Designed by NASA's MSFC and built by The Boeing Company in Huntsville, Alabama, an EXPRESS Rack is a refrigerator-size facility designed to support remotely operated science payloads by housing them and providing standard interfaces to the varied resources available from the ISS. Today there are five EXPRESS Racks onboard ISS supporting various scientific investigations. Experiments performed since Increment 2 through the present span the spectrum of scientific research including research and technology investigations, microgravity crystal growth for biological and commercial applications, astro-agriculture experiments, human and cellular life sciences, materials science, as well as devices providing ancillary data to the scientific community for analysis.

This paper briefly describes the components of an EXPRESS Rack and its operational capabilities. It also provides an overview of the test and development facilities used to support, troubleshoot, and improve performance. A few case studies of performance limitations that were encountered during on-orbit operations will be discussed along with the improvements made. Finally, the paper concludes with a description of planned enhancements.

[1] U.S. Government work not protected by U.S. Copyright
[2] IEEEAC paper #1139, Final Version , Updated December 1, 2004

Before launching into a lengthy discussion about EXPRESS Rack capabilities and upgrades, it is important to understand the history and development of the EXPRESS Rack with respect to crew operations. The first EXPRESS prototype flew on SpaceLab missions STS 83 & 94 in 1997 and was very similar to the racks onboard ISS today. It was designed with an operational concept of ample crew time dedicated to science operations. Unfortunately, that crew model has not been accurate for operations on ISS to date because of the limited crew sizes and the large number of station dedicated tasks they are required to perform. In fact, crew time is a factor that drives almost every aspect of science operations on ISS. During Increments 1-6, there were three crew members and in general this allowed sufficient time for scientific operations. Even so, every activity is prioritized according to scientific return and tasks needing as little as five minutes of crew time are scheduled according to science priorities. Since the Columbia accident, ISS crews have been limited to just two members, putting even more strain on crew availability to support payload science. This leaves little crew time for payload maintenance and anomaly recovery thus, minimizing and/or eliminating the need for crew has been a driving force in EXPRESS Rack development.

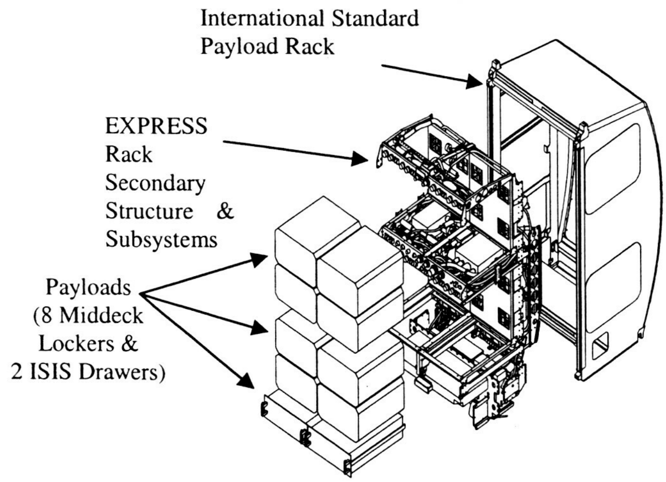

Figure 1 - EXPRESS Rack Exploded View

2. EXPRESS Rack Development and Testing Facilities

The standard EXPRESS Rack offers two types of accommodations for payloads: a Space Shuttle middeck locker sized interface and an International Subrack Interface Standard (ISIS) drawer interface. An EXPRESS Rack can accommodate eight middeck lockers and two ISIS drawers, hence the designation commonly referred to as an 8/2 EXPRESS Rack [1]. Refer to the exploded view of an EXPRESS Rack in Figure 1. Each EXPRESS Rack can support up to eight powered middeck locker and two powered ISIS drawer payloads simultaneously. Payloads that utilize one or more middeck locker spaces have available to them through cable connections to the front of the rack the following resources: 28V electrical power, full duplex data (Ethernet or RS-422), video output, water for thermal cooling, gaseous nitrogen, and two vacuum sources (for exhaust of experiment by-products and for 'clean' sustained vacuum). Figure 2 shows a picture of a single middeck locker payload, the Active Rack Isolation System Payload Onboard Processor installed in EXPRESS Rack 2.

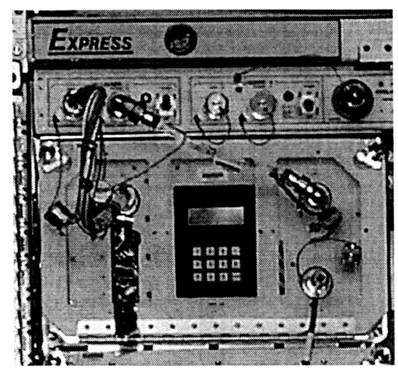

Figure 2 - A Single Middeck Locker Payload

Payloads installed in ISIS drawers have access to the same electrical and data connections but their interfaces are via blind-mate connections at the rear of the drawers. Figure 3 shows elements of the Space Acceleration Measurement System (SAMS) installed in the two ISIS drawers.

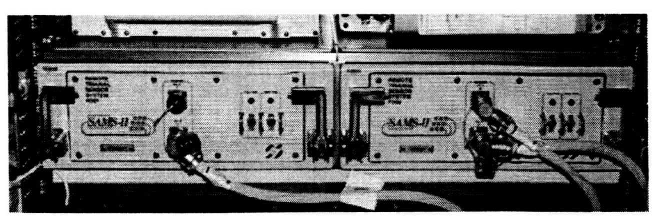

Figure 3 - Payloads Installed In The ISIS Drawers

Several technical papers and documents have been written describing the components of the 8/2 EXPRESS Rack. Therefore we have chosen to simply list the major components and their basic functions. See the reference section for a list of published documentation on EXPRESS Rack components [2, 3].

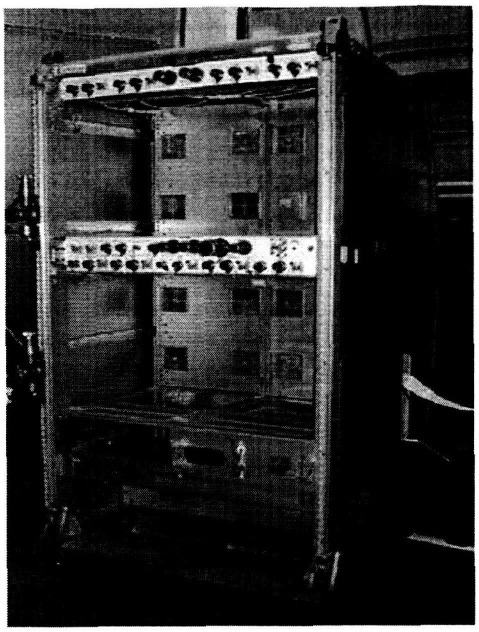

Figure 4 - EXPRESS Rack Before Payload Integration

Figure 4 shows an empty EXPRESS Rack prior to payload integration. While it appears to be just a shell, many complex components are installed efficiently behind closeout panels. The most important component is the Rack Interface Controller (RIC), the "electronic brain" of the rack. It is responsible for handling commands, routing telemetry and overall control of the sub-rack avionics systems. Other rack components include a Solid State Power Controller Module (SSPCM) which distributes 120 V and 28 V electrical power throughout the rack; an EXPRESS Memory Unit (EMU) which is a solid-state mass storage device providing up to 320 MB of data storage; a Payload Ethernet Hub/Bridge (PEHB) that routes data within the rack and to/from the ISS payload Local Area Networks (LANs), an Avionics Air Assembly (AAA) that provides air cooling for rack components, payloads and supports smoke detection within the rack; an EXPRESS Laptop Computer (ELC) (an IBM 760 XD Thinkpad) provides a convenient means for the ISS crew to command and check status of the rack and payloads; and finally the Utility Drawer at the bottom of the rack for storing cables and other rack hardware.

In addition to the resources listed above, EXPRESS Racks 2 and 3 have the capability of reducing the effects of vibrations from ISS subsystems or crew on their payloads. This is done with a closed-loop reaction force control system called the Active Rack Isolation System or ARIS [4, 5]. For these racks, additional components include an ARIS Controller, three tri-axial accelerometers and eight single axis electro-mechanical actuators and pushrods that impart forces reducing unwanted vibrations that could disturb sensitive microgravity science experiments in the rack.

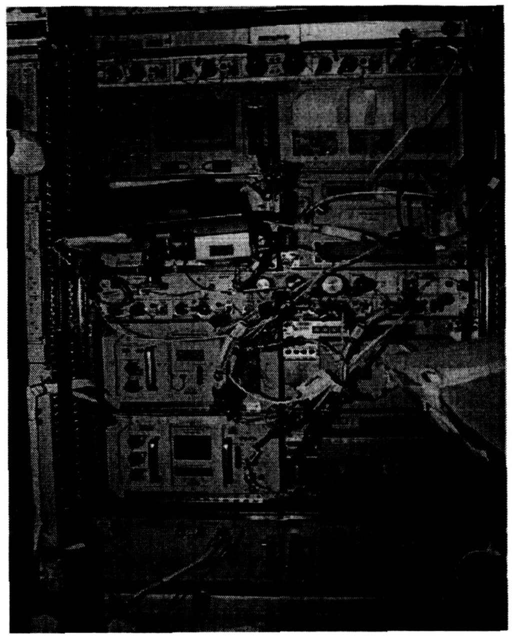

Figure 5 - EXPRESS Rack 4 Onboard ISS

Figure 5 shows a front view of EXPRESS Rack 4 in the Destiny Laboratory with a full complement of eight middeck locker and two ISIS drawer payloads installed, cabled and supporting science operations.

While it is always interesting to discuss space hardware, for successful engineering and operation of complex hardware such as this, it is just as important to understand how and where it is designed and tested. The Avionics Test Bed (ATB), designed and built by Boeing at MSFC, is one of the prime facilities used during the development phase of the EXPRESS program. It served as the main development platform for all EXPRESS RIC and ELC software. Currently the ATB is supporting the development of EXPRESS Rack derivative software.

The ATB encompasses an entire complement of EXPRESS Rack Functional Equivalent Units (FEU), as well as selected ISS subsystem and several payload simulators. EXPRESS FEUs include the RIC, SSPCM, EMU, PEHB and the ELC. The lab also includes ISS and EXPRESS system simulations that execute on a SUN workstation resident in the facility and are used to simulate the Command and Control (C&C) and Payload Multiplexer/DeMultiplexer (MDM) ISS Computers. Other computers are used to simulate Ethernet and RS-422 payloads. Figure 6 shows the ATB with EXPRESS components connected during development.

Figure 6 - EXPRESS Software Avionics Test Bed

As the EXPRESS Program continued to expand, additional EXPRESS Rack derivatives were being developed by NASA and Boeing. The ATB soon became a limited resource to support development, test, and verification activities. The EXPRESS program migrated all development and testing to the Payload Software Integration and Verification Facility (PSIVF), also located at MSFC. The EXPRESS Program, now in a sustaining mode of operation, utilizes the PSIVF to develop and validate on-board crew procedures, train ground controllers, and support real-time anomaly investigations.

The PSIVF encompasses several ground payload racks comprised of FEU, flight components, ISS system simulations, and payload simulations. The lab's FEUs include the Payload MDM, Portable Computer System (PCS), ELC, and Payload Ethernet Hub Gateway (PEHG). The facility also utilizes a flight qualified PEHB for rack-to-rack communications. Several RICs are resident in the facility and are classified as Qualification, Prototype and FEU. Flight qualified software is loaded and executed on the Payload MDM FEU, PCS FEU, ELC, PEHB, and the RIC units. System simulations execute on a Silicon Graphics workstation in the facility and are used to model the behavior of the EXPRESS Rack, ISS Payloads, EXPRESS payloads, SSPCM, AAA, and the Automated Payload Switch (APS) systems. A Command and Control (C&C) simulator is also provided to control the test environment, i.e., the Payload MDM, RIC, payloads, PEHG, and PEHB. A SUN workstation houses the control interface software that is used to direct and monitor the simulation activities. Computers with the Linux operating system are utilized to provide Ethernet and RS-422 payload simulations. A picture of some of the PSIVF rack components is shown in Figure 7.

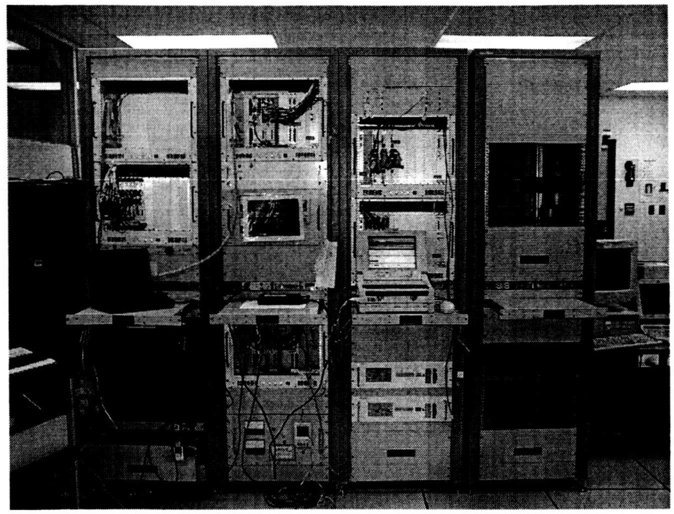

Figure 7 - Rack Development Platforms in the PSIVF

The ISS Payload Operations and Integration Center (POIC) at MSFC resides in a facility commonly known as the Huntsville Operations Support Center (HOSC). To support operations products and pre-mission testing, the HOSC and PSIVF are commonly configured to operate as one test facility. This allows the ground controllers to send commands directly from the software platforms they use for real-time ops to the FEU hardware and software in the PSIVF. Testing activities include verifying command and telemetry interfaces between the HOSC and PSIVF, verification of ground procedures, ground controller training, certification of flight readiness (CoFR), testing of HOSC systems and on-orbit anomaly resolution.

After an EXPRESS Rack has been assembled and all its components tested at MSFC, it is shipped to the Kennedy Space Center (KSC) for prelaunch integration. The EXPRESS Racks are launched to the ISS stowed in the Multi-Purpose Logistics Module (MPLM) in the Space Shuttle cargo bay. Prior to launch, the EXPRESS Racks and their payloads go though a series of integration tests to verify they will work properly with the other US Lab components when installed in the ISS.

Upon arrival at KSC, an EXPRESS Rack is tested in the Payload Rack Checkout Unit (PRCU). The PRCU provides a high fidelity emulation of the ISS interfaces to the payload rack including the power, cooling water, vacuum, gas, Fire Detection System (FDS), 1553 bus, Medium Rate Data Link (MRDL) and High Rate Data Link (HRDL) services. A Graphical User Interface (GUI) allows the test team to control all of the services being provided and to send commands and monitor telemetry from the rack.

After successful testing in the PRCU the payload rack is then transferred to KSC's Payload Test and Checkout System (PTCS). The PTCS is used for final functional checkout of all payload and payload rack to ISS interfaces operating in the US Lab, International Partner modules, the truss, or exposed facilities. This integrated testing is done with high fidelity compliment of FEU hardware. The PTCS tests a local "end-to-end" checkout of ISS payloads to ground system interfaces with simulated telemetry down-link to the payload developer and command and control uplink to the payload. The PTCS is configured with the Flight Quality Tested (FQT) software.

Pre-test preparation includes configuration and check out of PTCS, User/Control Room, payload, and Ground Support Equipment (GSE). Also, any required electrical cable checks are performed prior to powered test operations. After all preparations are complete, the PTCS and payload are activated to satisfy test requirements and objectives. Post-test securing involves power down and reconfiguration of the payload, PTCS, GSE and Control/User Rooms. PTCS can support multiple (up to eight) rack checkouts with all flight-like ISS subsystem interfaces including: fluids, structures, power, GN2, vacuum exhaust and resource, video, communication and tracking, and command and data handling. The PTCS has also been used to help resolve on-orbit payload anomalies when high-fidelity FEUs and ISS interfaces were required.

Following a successful test series in the PTCS, an EXPRESS Rack and its payloads are loaded into a MPLM which is then installed in the cargo bay of the Space Shuttle for launch. MPLMs provide a pressurized environment for the payloads and racks during their flight to the ISS. After being berthed to the ISS, the MPLM is unloaded by the ISS crew. New payload racks are transferred carefully by the crew and then installed in their designated location in the US Lab.

3. EXPRESS Operations Begin on ISS

With the launch of the ISS Increment Two crew members on March 8, 2001, the POIC at MSFC (shown in Figure 8) began around-the-clock operations serving as the world's primary science command post for the Space Station, linking Earth-bound researchers around the world with their experiments and astronauts aboard the ISS [6]. Later that Increment, Space Shuttle Flights STS-100 (ISS Flight 6A) delivered EXPRESS Racks 1 and 2 to ISS in April 2001 and STS-105 (ISS Flight 7A.1) delivered EXPRESS Racks 4 and 5 in August of 2001. Within days of arriving onboard the ISS, the EXPRESS Racks were installed in the US Lab by the astronauts and the science experiments were activated. During the checkout period that followed, all the software development and testing done on the ground paid dividends as there were only a few technical problems.

Figure 8 - The Payload Operations and Integration Center

During the initial months of operation, several EXPRESS Rack payloads were active including: an experiment called Advanced Astroculture (ADVASC) that grew plants in a complete seed-to-seed cycle to assess the impact of space flight on gene expression; a biotechnology experiment called Commercial Generic Bioprocessing Apparatus (CGBA) that provided a temperature-controlled environment for a wide variety of biotechnology experiments; the Commercial Protein Crystal Growth (CPCG) payload which consisted of 1,008 individual experiments that studied protein crystals in microgravity to improve pharmaceutical processes; also installed in EXPRESS Racks 1 and 2 were the Microgravity Acceleration Measurement System (MAMS) and the Space Acceleration Measurement System (SAMS) payloads that help scientists track and understand the tiny disturbances felt by their experiments while onboard ISS.

EXPRESS Racks are primarily operated from the ground by a Payload Rack Officer (PRO) on-duty at the POIC. Alternatively, the racks can be controlled by the ISS crew via the ELCs, but due to the extreme constraints on crew time discussed above; crew commanding of the EXPRESS Rack is only performed if commands cannot be uplinked from the ground. The PRO monitors the rack status and supports experiment operations seven days a week, 24 hours a day. He/she sends commands to the payload racks to maintain the desired temperature control, data processing, and software configurations. It is also important to recognize that EXPRESS Racks give scientists and engineers the ability to command directly to their experiments. The experimenters issue commands from their labs and the data is routed to the POIC for validation. From there the command data is routed to the ISS Mission Control Center in Houston where it is uplinked to the ISS. Likewise, the data from experiments on the ISS is down-linked to the ground and routed back to the principal investigator's lab. This method of conducting remote science is much more convenient and efficient than methods in the past.

While for the most part, the initial activation of EXPRESS Racks 1 and 2 went smoothly, one operational limitation that plagued the ground operators and the payload science community was the racks' tendency to stop transmitting telemetry during heavy data loading. To ground controllers it appeared that the RIC simply "locked up" from time to time; similar to when a desktop PC freezes. To recover, the crew and ground controllers did what we would do to our PC's – they rebooted it by pushing a switch that the EXPRESS Rack designers had the foresight to include. (See Figure 9) However this task was complicated by the fact that some payloads required water cooling and if the commanding required to recover from the reboot was not finished promptly, the experiments would be ruined. Fortunately, the ground controllers were able to closely coordinate with the crew to perform the manual reboots during periods of adequate communication with the ISS.

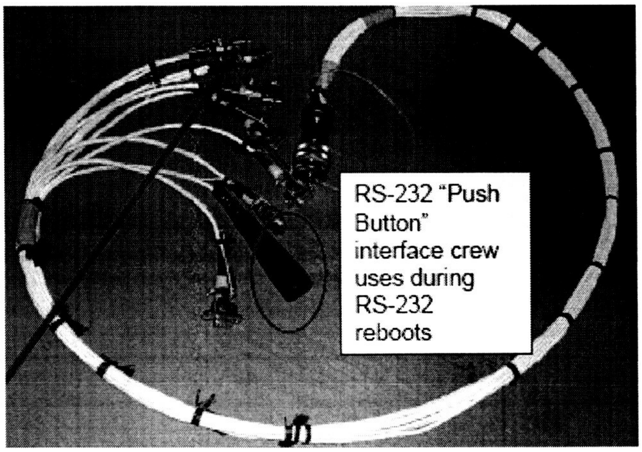

Figure 9 - EXPRESS RS-232 Cable and Reboot Switch

To understand this problem, one must first know more about the EXPRESS RIC. The RIC is designed to support multiple Ethernet and RS-422 payloads simultaneously. The RIC architecture is quite complex and is comprised of several Versa Module Euro (VME) cards interconnected via a backplane. Each of the VME cards have unique responsibilities such as processing command, and telemetry data for Ethernet and/or RS-422 payloads, transmitting telemetry packets on a LAN via raw Ethernet packets, transmitting telemetry packets via fiber optic, communicating with the next higher tier station computer system. During analysis, the RIC "lock-up" problem seemed to be most prevalent when the EXPRESS Rack's internal communications LAN reached a data saturation level. After several "lock-ups" were observed, engineers on the ground identified problems which were isolated to the RIC VME card responsible for receiving raw Ethernet packets from each payload and inserting them into a single telemetry stream sent to the ground.

Through ground testing, the problem was isolated to firmware on the VME cards which handle transmitting raw Ethernet telemetry packets. The problem occurred when the firmware's First-In First-Out (FIFO) data buffer became empty because the data was transmitted onto the LAN faster than it was being received by the memory subsystem. The chip detected the condition and generated an interrupt to the device driver, basically rebooting the chip. When this happened, transmission of raw Ethernet data was automatically disabled. Unfortunately, the device driver responsible for recovering from the underflow condition failed to recover and thus the RIC never was aware of the problem and continued attempting to transmit raw Ethernet telemetry packets.

Redesign of the chip's device driver module focused on rotating the FIFO buffer so that the outgoing packet which failed ends up in element zero. The circular buffer was set to index at element zero, and the CPU is set to index at the first empty ring element. When the chip is restarted, operations continue from where the failure occurred, and the processor is able to successfully add new packets to the buffer. Numerous test sessions proved that the chip's redesign worked, the new software was released as EXPRESS Rack Software load Release 2 and loaded on-orbit in September of 2001.

4. SCIENCE OPERATIONS IN FULL SWING

During Increments 3 through 6, new EXPRESS Rack payloads were being regularly flown to ISS on the Space Shuttle. Some of these included the Dynamically Controlled Protein Crystal Growth (DCPCG) experiment, the Zeolite Crystal Growth (ZCG) furnace and the ARIS-ISS Characterization Experiment (ARIS-ICE). Some of these required a "high" throughput rate and data volume for transmission to the ground to support near real-time science. An example of this was DCPCG, a double middeck locker payload. This experiment's objective was to refine the methods for growing biological macromolecules using dynamic control of a protein solution. This dynamic control led to the requirement for down-linking large digital picture files quickly for analysis so the scientist could uplink their next set of control commands.

It was during this period that the PROs discovered that the EXPRESS Rack's High Rate Telemetry (HRT) mode was unable to support the throughput rate requested by DCPCG.

It was also discovered that if the EXPRESS Rack's HRT link was left active for longer than several hours, telemetry would stop all together and a RIC reboot would be required. Fortunately, the PROs were able to meet the scientist's minimum data rate requirement by using the EXPRESS Rack's medium rate mode.

The challenge in solving the high rate problem was finding a way to characterize the rack's performance on the ground in an attempt to isolate the problems on orbit. Several tests were performed in the PSIVF using the flight qualified RIC loaded with flight software and payload simulators similar to DCPCG. Ultimately these tests indicated that the RIC's high rate software was failing to add telemetry packets to its storage array when the VME backplane became saturated. The software stopped transmitting data to the Field Programmable Gate Array (FPGA)/FIFO and the storage buffer eventually filled up. The ultimate effect was that the HRT link stopped transmitting data out of the rack. The RIC's HRT link was redesigned to remove the packet storage buffer due to the fact that the firmware FIFOs could process the data packets as quickly as the application software could send the packets.

Additionally, it appeared that the efficiency of the RIC's VME backplane severely degraded as payloads increased the amount of traffic on the backplane. The VME backplane efficiency was improved by modifying the RIC's high rate link card VME controller to change the method in which the FIFOs operated. The VME Controller was modified to transmit the data only when the FIFO is full and therefore drastically decreased the frequency at which the controller accesses the bus. Accessing the VME bus less equated to increasing the time the bus could be used by other RIC VME cards and processes. The RIC's VME cards were also modified to manage the bursts per block and interleave period parameters which initialize the chips for processing. The bursts per block is the number of writes to the VME bus per burst and the interleave period is the time between bursts. The overall effect is that more data can be sent across the VME backplane each time the VME controller gained access to the bus, thus decreasing the number of times the VME controller has to access the bus to transmit an entire message or data set. The VME and local bus timeout periods were changed to allow the bus to be freed sooner should a RIC's VME Controller require access to the bus for an extended period of time. After the above software modifications were made and numerous test sessions proved that the redesigns worked, the new software was released as EXPRESS Rack Software load Release 3 and loaded on-orbit in January of 2003.

5. After The loss Of Columbia

As the Increment 6 crew members were nearing the end of their stay on ISS, the tragic loss of the Space Shuttle Columbia and her crew stunned the world. It also brought drastic changes to the ISS community. The primary method for transporting EXPRESS Racks and their payloads was via the Space Shuttle. Grounding of the shuttle fleet slowed the steady flow of new experiments to ISS to a trickle. Another major impact was that subsequent crews were limited to two people, putting further strain on crew time requirements.

Prior to the Columbia accident, most EXPRESS Rack improvements focused on throughput handling and sizing of payload science data through software changes. Since the tragic loss of Columbia, efforts have focused on reducing the amount of crew time required in operating the EXPRESS Racks and payloads. Ground operators are also identifying what common and reoccurring tasks performed by crew can be transferred to ground operators or automated through software.

Other than loading upgrades of EXPRESS Rack software, the single most reoccurring activity the crew performs to support EXPRESS Rack operations is rebooting the RICs and ELCs. The ELC (see Figure 10) is not radiation hardened and is prone to file corruption. PROs perform periodic directory listings of the ELC and when a response is not received on the ground, the crew is requested to check the ELC for a blue or black "Screen of Death". A blue "Screen of Death" is normally symptomatic of a failure with the ELC's operating system; a black "Screen of Death" is indicative of a catastrophic failure such as a power loss, a core element of the ELC hardware (CPU, motherboard, video card) failing, or a radiation hit on the memory causing the ELC to lose its operational context. In either case, the crew is requested by the ground to reboot the ELC which normally recovers functionality. If the ELC is not restored, the crew is asked to reload the ELC's hard drive. An enhancement has been added to the EXPRESS ELC software such that should a blue "Screen of Death" occur, the operating system crash data is stored in a user defined location which can be later down-linked to the ground for analysis. Additionally, the ELC is configured to automatically reboot after logging the system crash data, thus eliminating the need for crew involvement. Unfortunately this software enhancement does not help in the event of a black "Screen of Death" because the operating system is unable to handle to ELC's failure and therefore cannot execute the reboot. The ELC does not currently have a remote reboot capability which can be commanded from the ground, but is an enhancement that is being considered for a future software release.

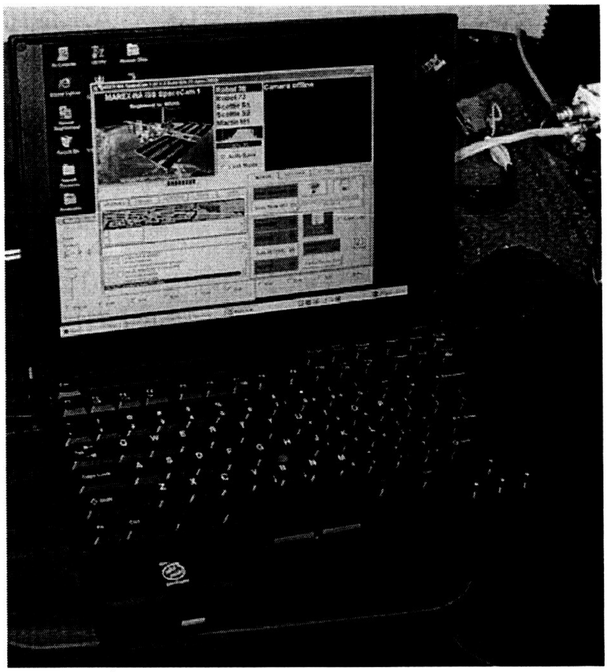

Figure 10 - IBM 760XD EXPRESS Laptop Computer

A significant enhancement added in the latest version (release 4) of EXPRESS RIC software is the capability for the ground to command a RIC reboot without powering off payloads. Prior to release 4, if ground operators wanted to reboot the RIC without the crew, they essentially had to power cycle the entire rack, which meant loss of power to the payloads. Otherwise they were forced to wait until the crew was available to perform a manual reboot. The new ground commanded reboot provides greater operational flexibility and reduces the need for crew time. This means that although payload science telemetry to the ground is interrupted for a short period during the reboot, the payloads continue to operate and their data can be transmitted to the ground after the reboot is complete.

Additional enhancements were made to reduce crew time involved with the EXPRESS Rack software loading method. Recently there have been operational scenarios requiring a crew member to relocate an ELC to another EXPRESS Rack location. To do this, the crew must reconfigure the ELC for that rack before executing a software load. A utility was added to the EXPRESS ELC software that enables a crew member to select a specific rack from a list and based upon the selection, automatically configures the ELC in less than a minute to support the software load.

EXPRESS Rack software upgrades can either be loaded from a CD flown on a shuttle or by transferring the software to the ISS from the ground. Until recently, the main problem with uplinking software was that once onboard, the new software had to be transferred from one computer system to the ELC by the crew via floppy disks. With the grounding of the shuttle fleet, crew time and floppy disks became a scarce commodity on-board the ISS. Therefore, to reduce crew interaction of transferring EXPRESS RIC software onto an ELC, a self-extracting archive that could be transferred from the ground directly onto the ELC was developed.

As software upgrades were being integrated into future EXPRESS flight software loads, the issue surfaced concerning the amount of crew time that would be involved in loading the software. The primary components of the EXPRESS Rack architecture which have the capability of upgrading software without having to replace the hardware component are the RIC, which has programmable flash memory, and the ELC which is an IBM 760XD ThinkPad. Prior to launch, the ground procedures used to load software onto the EXPRESS RIC and ELC were extremely long and required an immense amount of human interaction. The loading of an EXPRESS RIC and ELC combined took approximately 8 hours for an experienced technician and more than 500 procedure steps to execute. This load process was too time consuming in terms of crew time and was prone to human error.

To address these issues, Boeing investigated ways to automate the process thereby loading the software faster. They arrived at a solution that utilized a commercial-off-the-shelf (COTS) application that ran on the ELC with scripts. The scripts loaded the EXPRESS RIC software via a single RS-232 connection from the ELC to each of the four RIC cards. Using this method, it took 3 hours to completely load the RIC, but because it was done automatically by the scripts, very little crew time was required during the loading process. Additionally, scripting the load with menu driven instructions reduced the likelihood of corrupting the load by user error. Unfortunately, it still took 5 hours of crew intensive procedures to load the ELC. In September 2001, the first EXPRESS RIC software upgrades (Release 2) were loaded onto EXPRESS Racks 1 and 2.

For the next software release, Boeing engineers set out to reduce the time and crew steps required to load the ELC software. They was able to decrease the load time from 4 hours to just 15 minutes by using another COTS product to create and restore an image of an ELC's hard drive from a CD. In January 2003, the first EXPRESS ELC software upgrade (combined load release 3) was successfully loaded onto EXPRESS Racks 1, 2, 3, 4, and 5 by the astronauts using this process.

Additional improvements in the EXPRESS RIC's software load procedure were made to address the 3 hours required to load an EXPRESS RIC. A new COTS PCMCIA card/cable assembly was acquired and tested which provided 4 external serial ports to the ELC. The script to load the RIC's software was modified to load all 4 RIC cards simultaneously. This reduced the RIC load time from 3 hours down to 45 minutes. In January of 2003, EXPRESS RICs 1, 3, 4, and 5 were loaded with release 3 software.

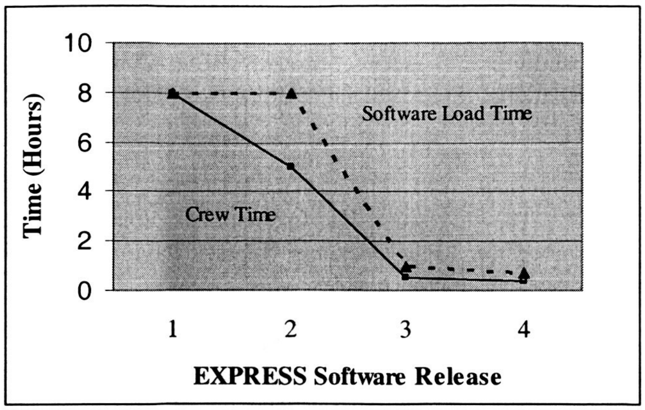

Figure 11 – Comparison of Crew and Total Time Required Per EXPRESS Rack Software Release Version

Ultimately both goals of reducing the crew time required and the amount of human intervention needed for the EXPRESS Rack software load activity were met. The time to load both EXPRESS RIC and ELC software has gone from an original time of 8 hours, to just 30 minutes of crew time. It is also worth noting that while crew time is the most valuable resource on orbit, these improvements have also led to saving hundreds of man hours on the ground for software developers, testers, and technicians.

6. The Future for ISS Payload Science

Today, the EXPRESS Racks are considered reliable platforms with which scientists can conduct their experiments remotely. However from time to time, they still experience lock-ups and single event upsets. There are work-arounds to these infrequent events but the EXPRESS Team is working hard to eliminate these impacts.

As discussed above, the EXPRESS ELC has shown a susceptibility to lock-up frequently due to radiation events. In response to this the ISS program is upgrading all ISS based support and payloads computers from the 760 XD to the IBM A31P, also referred to as the Next Generation Laptop (NGL). There are a small number of these already onboard ISS and these have shown more resistance to lock-ups. The NGL also offers the opportunity to move closer to the computer industry's state-of-the-art platform and operating system. In the coming months, all EXPRESS ELCs will be transitioned to the NGLs. Another capability being seriously studied is to provide ground controllers the ability to remotely reboot the NGLs.

Another high-priority future enhancement is to improve the EXPRESS Rack RIC. The current RIC is based upon the Motorola 33 MHz 68030 processor. This architecture is starting to impose throughput limitations on proposed science experiments. Currently NASA and Boeing are in the initial stages of upgrade studies for the RIC. A goal of these studies is to increase the RIC's throughput and data handling capability by tenfold.

Future EXPRESS software enhancements will also focus on sizing, timing, and total throughput to expand the operational capabilities to support continuous operations while simultaneously reducing crew member involvement. One example on the horizon is the ability for the EXPRESS RIC software to autonomously reconfigure the rack for normal operations after a reboot without ground or crew commanding. Currently, the PROs have to configure an EXPRESS Rack after a power cycle or reboot which can take from 10 to 30 minutes. Additionally, sufficient S and Ku Band communication coverage is required to recover the rack and therefore telemetry outages could take even longer. With this new capability, the time from reboot to recovery will be reduced to just a couple of minutes regardless of communication coverage.

A final yet important type of upgrade being considered for the EXPRESS Rack is for ways to make it easier for scientists to integrate their payloads with the RIC. Currently all EXPRESS payloads must adhere to the EXPRESS software Interface Control Document (ICD) which is very sophisticated and includes a specific data header requirement for RIC communications. This implies a great deal of coding expertise that can impose schedule and cost impacts to small, non-complex experiments that only require power and a simple path to send data to the ground. Investigations are underway to possibly use COTS Ethernet programs and protocols that would ease the software engineering requirements from the scientists.

7. Conclusion

This paper highlights the accomplishments of the payload engineering and operations teams to make the EXPRESS Rack a stable and robust science facility. Improvements have been made to increase the RIC's data handling capabilities through software upgrades. The teams' have also drastically reduced the crew time required to load software and operate the racks. The improvement in particular has allowed the ISS crews more time to perform science experiments by spending less time on infrastructure maintenance. Future EXPRESS Rack enhancements will focus on hardware upgrades to increase resistance to radiation lockups and higher data throughput capability.

The EXPRESS Rack Program and the science payloads that have operated within them have been tremendously successful. Like any endeavor, there have been set backs and some progress has not come as quickly as expected. However, looking back over the four years of science operations onboard the ISS, it is easy to recognize that great strides have been made in the ability to remotely support payload science, resolve anomalies and provide an excellent facility to perform new and innovative experiments in low Earth orbit.

As the Space Shuttle fleet returns to flight and construction of the ISS begins again, so too will the steady stream of science payloads. In the coming months and years, additional science racks will be sent to ISS. Many of these will be variations on the EXPRESS Rack design. These racks in turn will help earthbound scientists to conduct their experiments remotely in the microgravity environment of low Earth orbit.

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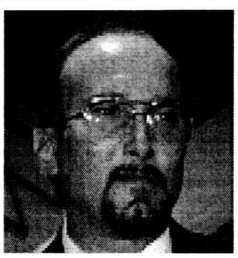
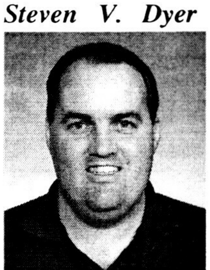
Biography

Craig A. Cruzen *is a Payload Operations Director (POD) at NASA's Marshall Space Flight Center in Huntsville, AL, where he leads the ground control team in performing science operations onboard the International Space Station. Before being selected as a POD in 2003, he served as an ISS Payload Rack Officer (PRO) and Timeline Change Officer (TCO). Duties in these flight control positions included monitoring and commanding payload racks and payload support systems onboard the ISS as well as maintaining daily activity timelines. Prior to joining the payload operations team, Mr. Cruzen was a guidance and navigation systems engineer where he worked on the Space Shuttle program, NASA's Automated Rendezvous and Capture project as well as the X-33 and X-37 vehicle development programs. He holds a Bachelors degree in Aerospace Engineering from the University of Michigan in Ann Arbor.*



Richard E. Gibbs III *is an Embedded Software Design/Systems Engineer at NASA's Marshall Space Flight Center in Huntsville, AL. He is employed by The Boeing Company as the lead support engineer to real-time payload operations and resolution of software anomalies. Mr. Gibbs has been supporting the ISS Program for fourteen years and specializes in Fault Detection, Isolation, and Recovery (FDIR) for large integrated systems. Prior to entering the space industry, he supported military defensive ground launch systems and specialized in the area of guidance and control. He received his Bachelor's of Science in Computer Science from Mississippi State University.*



Steven V. Dyer *is the Operations Lead for the ISS EXPRESS Rack Facility. In this role, he is responsible for leading the development of EXPRESS rack operation, planning, preparing the PROs to support increment operations, assessing rack operations, and coordinating troubleshooting activities. Mr. Dyer has also provided civil service oversight and technical coordination for the development and update of EXPRESS rack crew procedures and the impact of rack technical changes to operations. Prior to joining NASA in 2000, Mr. Dyer was an officer in the United States Coast Guard. He holds a Bachelors and Masters degree in Aerospace Engineering from Auburn University.*

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Acknowledgements

The authors would like to acknowledge the following groups who have contributed to the success of performing remote science onboard the International Space Station:

- The POIC operations team at MSFC who operate science payloads around the clock on ISS and at the same time plan for future experiments.
- The NASA/Boeing EXPRESS Rack development team without whose hard work and dedication, the EXPRESS Rack project would not be possible.
- The ground testing teams at MSFC and KSC who work to ensure that hardware and software launched into space is the best it can be.
- The astronauts and cosmonauts who live and work aboard the ISS and risk their lives in the pursuit of space exploration.
- The scientists and engineers who design the experiments and use the results to improve our way of life on Earth.